PRACTICAL METHOD TO MODEL TREES FOR DAYLIGHTING SIMULATION USING HEMISPHERICAL PHOTOGRAPHY

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ABSTRACT

The ability to simulate the effect of trees on natural light performance in buildings is contingent upon accurate simulation of light passing through the canopy. Accurate simulations require some assumption of leaf angle distribution to compute canopy gap fractions. The ellipsoidal leaf angle distribution can very closely approximate real plant canopies. The method requires calculation of leaf area density from observed distribution of gap fraction as a function of zenith angle. Hemispherical image acquisition and analysis is used to measure gap fractions. Based on the results, the gap fractions of a theoretical tree are predicted. The results will guide to develop a 3D tree model that can be used in lighting analysis software such as Radiance.

INTRODUCTION

The ideal window design is the one that admits only a small amount of sunlight through the windows in the summer and a maximum amount in the winter (Lechner, 2002). At all times, however, the light should be diffused by reflecting it off the ceiling. If that is not possible, the light must be shaded before it enters. Plants can provide sun shading and improve the quality of daylight entering through windows by scattering direct sunlight and reducing its intensity while moderating glare coming from the bright sky. The same beneficial effect can be achieved by vines across the windows or trees farther away. Quality daylight is achieved by blocking direct sunlight while encouraging reflected sunlight. Since light reflected off the ground penetrates deeper into a building than direct light, it is sometimes desirable not to have vegetation right outside a window on the ground. Sunlight can be filtered and softened by trees or by such devices as trellises and screens. These natural methods (i.e., plants and trees) provide better quality of daylight than the use of light drapes or translucent glazing because of the problem of glare. In addition to improvements in lighting environments, plants and vegetation can provide other environmental benefits: create a better microclimate in courtyards and outdoor spaces with the modified thermal conditions as a result of shading and passive cooling; provide esthetics in the indoor and outdoor spaces; reduce noise levels; provide healthier spaces and filter air from dust and unhealthy particles; and improve thermal and visual comfort and improve well being.

To simulate a luminous environment with the effect of trees using software (such as Radiance), one would need to develop appropriate three-dimensional model of certain types of trees that closely represent actual ones. To do this, several characteristics, such as size of the tree, leaf area, and reflectance of leaves, must be known. Some data are available and can be collected directly from the literature such as the size and geometrical characteristics of the tree. Other data such as leaf area and its pattern of distribution is hard to find. Estimating these types of data based on observation and field measurement is a difficult task that could lead to doubtful results. This could also become very tedious and impractical if it is repeated over a large number of trees. Moreover, the variation of these characteristics from one tree to another of the same type is enormous. Hemispherical tree photography and image analysis software provides an alternative practical method to measure characteristics of tree canopies. It is widely used in agriculture and plant biology research.

BACKGROUND

Measurement of specific characteristics of trees is an area of research that is rarely touched by scholars in architecture or building science. Research in other fields such as forestry research and agriculture presents a valuable resource with regard to methods and tools of trees' measurement. A byproduct of measuring the dissipation of light as it penetrates a tree canopy is an estimation of the cumulative Leaf area index. LAI is widely used to describe the photosynthetic and transpirational surface of plant canopies. LAI; expressed in m2 leaves area/m2 of covered ground, has broad applications in ecophysiology, water balance modelling, and characterisation of vegetation atmosphere interactions. In recent years, many researchers have adopted the definition of LAI as half of the total leaf area per unit ground surface area (Lang et al. 1991, Chen and Black 1992, Rich et al. 1999), as opposed to the projected area, which does not work well for all leaf shapes.

Bellow and Nair's study (2002) investigated regulating the shade provided by overstory trees in the management of shaded-perennial agroforestry systems. It compared the merits of commonly used light-assessment techniques and quantified the extent of shading in multistrata agroforestry systems, by measuring understory photosynthetically active radiation (PAR) beneath 28 single-species and four mixed-species stands of trees in Costa Rica. Canopy gap fraction was estimated by three methods in each stand: densiometer, visual index, and hemispherical photography. The gap fractions so derived were compared as estimators of mid-day PAR transmission. Of the techniques, gap fractions using densiometers were the most predictive, except under conditions of low stand density (<500 trees per hectare) and open canopies, where estimates from hemispherical photograph were better.

Lin and Chiang (2002) used hemispherical photographs to study recovery rates of forest canopies after disturbance, seedling growth, habitat quality, forest productivity, and plant ecophysiology. They stated that undercanopy hemispherical photographs provide permanent records of canopy structure, and as such have great potential for studies of forest canopy dynamics. Rapid computerized image analysis has facilitated studies of undercanopy light environments and the canopy leaf area index (LAI). The orientation and range of hemispherical photographs greatly affect estimates of light indices. A self-leveling mount equipped with an LED (light-emitting diode) was used to level the hemispherical lens and to identify the range of the image. Obtaining images with high contrast can save time and increase the efficiency and accuracy of the image analysis. In addition, the light environment estimated from hemispherical photographs does not take into account sky conditions, so such data from different sites must be compared with care.

Simulation the effect of trees on lighting performance in buildings requires finding effective mathematical models capable of representing specific measured canopy characteristics (such as the ones explained above). The purpose of this research is to demonstrate a practical method that integrates data acquisition and analysis with lighting simulation in the built environment based on appropriate mathematical models that can compute lighting interception of tree canopies.

THEORY

Calculation of LAI involves use of Beer's Law, which can be expressed as follows:

$$G(\theta) = \exp(-K(\theta) \, . \, L) \qquad (1)$$

Where G is gap fraction, K(θ) is the extinction coefficient at angle θ, and L is LAI, θ is zenith angle. Gap fraction is the proportion of visible sky within a given sky sector, where a sky sector is defined by a range of zenith and azimuth angles. A gap fraction of zero (0) means that the sky is completely blocked (obscured) in that sky sector. A gap fraction of one (1) means that the sky is completely visible (not obscured) in that sky sector.

Campbell (1986) derived a straightforward value for the extinction coefficient for an infinite uniform canopy of randomly oriented leaf elements, of given LAI and an ellipsoidal leaf angle distribution. This allowed the leaf angle distribution to be described by a single parameter, the Ellipsoidal Leaf Angle Distribution Parameter or ELADP. In this model, the leaf elements are distributed in the same proportions as the surface of an ellipsoid of revolution, where ELADP is the ratio of the horizontal to vertical axes of the ellipsoid.

For a canopy of LAI L and ELADP x, the extinction coefficient for a light ray passing through the canopy at zenith angle θ is given by the equation:

$$K(x,\theta) = \frac{\sqrt{x^2 + \tan(\theta)^2}}{x + 1.702\,(x + 1.12)^{-0.708}} \qquad (2)$$

Where x is the ELADP and θ is the zenith angle of the direct beam. The probability of the light ray passing through the canopy, or the gap fraction in that direction, can be expressed as follows:

$$\tau(x,\theta) = \exp(-K(x,\theta) \, . \, L) \qquad (3)$$

where τ is the gap fraction, L is the Leaf Area Index, and K(x,θ) is the extinction coefficient. The equation can be inverted to give an estimate of LAI; this would require finding the gap fraction using one of the measurement methods such as hemispherical photography or light interception. Calculation of LAI involves a kind of iterative "inversion" model, whereby LAI is inferred from the observed distribution of gap fraction as a function of zenith angle. The model finds the values of LAI and ELADP for an ellipsoidally distributed theoretical canopy that give the best fit to the measured gap fraction values. The model is completely independent of scale, so that the actual thickness of the canopy does not make any difference, only the total LAI of the whole canopy matters.

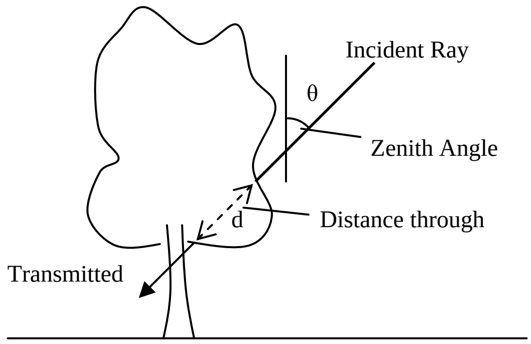

Figure 1 Ray passing through a canopy.

The probability of a ray of light passing through the canopy depends on the distance it has to travel through the crown (Figure 1). The extinction coefficient K(x,θ) defined above gives the extinction of a ray of light passing completely through a horizontal canopy. The extinction coefficient for a ray of light passing through unit canopy distance is given by:

$$G(x,\theta) = K(x,\theta)\cdot\cos(\theta) \quad (4)$$

and the gap fraction is now given by:

$$\tau(x,\theta) = \exp(-G(x,\theta).LD.d) \quad (5)$$

where d is the distance through the canopy and LD is the leaf area density, which is defined as the total area of (single sided) leaf surface per unit canopy volume. This equation can now be inverted to find LD (and ELADP) from the gap fraction values if we can estimate d, the distance through the canopy (tree crown) at the angle of each light ray (or hemispherical photo sector). One approach to finding the distances through the crown is to measure them. An easier approach is to assume the crown has a simple geometric shape and calculate the distances using trigonometry.

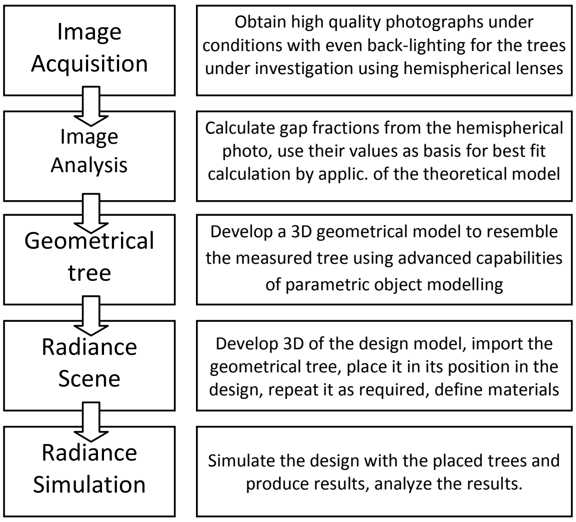

Figure 2 Illustration of the methodology/workflow.

METHODOLOGY

The methodology consists of five stages as shown in Figure 2. These are as follows:

Image Acquisition

Image acquisition involves taking hemispherical photographs using a film or digital camera looking upward from a location of interest (e.g. from beneath a plant canopy). When acquiring hemispherical canopy photographs in the field, the basic goal is to obtain high quality photographs. Photograph quality is critical. In general, it is best to take photographs under conditions with even back-lighting, in particular just before dawn or just after sunset, and on days with evenly overcast skies. A high quality hemispherical lens should be used. High quality hemispherical lenses and rugged cameras are manufactured by several companies, including Sigma, Canon, Minolta, and Nikon (Rich et al. 1999).

Image Analysis

Image analysis involves four steps: 1. classification of images to distinguish visible and obscured sky directions (e.g. for canopies, to distinguish canopy openings from foliage); 2. calculation of sky visibility and obstruction as a function of sky direction; 3. calculation of solar radiation and/or canopy indices using this information about sky visibility and obstruction; and 4. output of results. The gap fractions are calculated from the hemispherical photo and their values are used as basis for best fit calculation by application of the theoretical model mentioned earlier. The aim is to find the LD and ELADP (for an ellipsoidally distributed theoretical canopy; denoted here as EDTC) which, when combined with the geometry model, give the best fit to the measured gap fraction values. This is done using a "least squares" technique. The gap fractions of this new theoretical tree (EDTC) can then be predicted based on the calculated values of ELADP, Leaf Area Density, for the assumed crown geometry.

Development of Geometrical Tree

With the crown geometry and the predicted gap fractions data being available now, developing a three-dimensional geometrical model to resemble the measured tree is possible. The advanced capabilities of parametric object modelling existing in most current 3D modelling software nowadays helps to accurately develop/control solid surfaces that can represent tree canopies. The developed geometrical model of the tree canopy can be used in lighting simulation software such as Radiance to simulate its effect on lighting performance. *Radiance* is a computer software package developed by the Lighting Systems Research group at Lawrence Berkeley National Laboratory, University of California, under the direction of Greg Ward (Ward and Shakespeare, 1998). It is a research tool for accurately calculating and predicting the distribution of visible radiation by using a combination of ray-tracing and radiosity techniques.

Building a Radiance Scene

The first step in creating a Radiance scene is building a geometrical model of the physical world. The model created for the tree canopy surface along with other objects in the lighting environment is imported to Radiance (Radiance supports elaborate models and has translators for many design software). Another part of the scene description is the definition and application of materials for the objects in the scene. Material spectral properties include their color, reflective properties, and transmittance properties. It can be acquired from field measurement. The third part of the scene is the sky description, created by the 'gensky' generator. *Gensky* produces a *Radiance* scene description for the CIE (Commission Internationale de L`eclairage) standard sky distribution at the given month, day and time for any given geographical location.

Simulation with Radiance

Radiance uses a combination of ray-tracing and radiosity techniques to calculate and predict the distribution of visible radiation. The program generates spectral radiance values in the form of photo realistic images and numerical tables. Currently, the validation of the method concentrates only on the input parameter predicted from tree measurement, namely gap fraction. Validation of the simulation results against real measurement of lighting levels for a full scene is still necessary to prove the success of the model; it is an important issue that needs to be investigated in future research.

Figure 3 Hemispherical photograph of the real tree (a); superimposed on skymap sectors (b)

RESULTS AND DISCUSSION

The gap fractions from a hemispherical photograph (Figure 3) of a single tree are measured using a special software for this purpose, named Hemiview (Rich et al. 1999). Their values are associated with the sky map, based on division of the sky dome into eight segments in the azimuth direction (i.e.; every 45° azimuth angle) and nine segments in the zenith direction (i.e.; every 10° zenith angle); as described in Table 1. The crown of the tree is assumed to be as half ellipse shape with 4 meters height and 2 meters radius. The leaf area density (LD) and Ellipsoidal Leaf Angle Distribution Parameter (ELADP) are calculated based on the tree geometry and the best fit to the measured gap fraction values using equations 4 and 5. Based on the calculated values of ELADP, Leaf Area Density, and the assumed crown geometry, the gap fractions for an ellipsoidally distributed theoretical canopy is predicted (Table 1). These values along with the crown geometry (i.e., height and radius) helped to develop the geometrical model of the tree canopy using parametric object modelling.

A three-dimensional solid surface was built to represent the geometrical model of the tree canopy (Figure 4). The surface was constructed with 72 faces (i.e., 8×9) to correspond to the number of segments of the sky dome that was determined earlier. Doing this would help to create a correlation between the gap fractions that were predicted earlier using the mathematical model and the gap fractions that are needed for the geometrical model. To facilitate this, each face of the surface was modelled with meshing, and the values for the meshing density of each face were controlled to reflect the density of the gap fractions that were predicted earlier, taking into consideration the surface ratio needed for the solid parts. Frames were created along the meshing lines to represent the solid surface of the canopy. A hemispherical view of the developed object was taken using a virtual camera with 180° view angle that was placed in the centre of the object. The image was analyzed using Hemiview software and the gap fractions were estimated from this image (see Table 2).

(a) (b) (c)

Figure 4 Constructing the 3D canopy: creating the meshed surface (a); framing the mesh lines (b); and finally taking a hemispherical view to be analyzed (c)

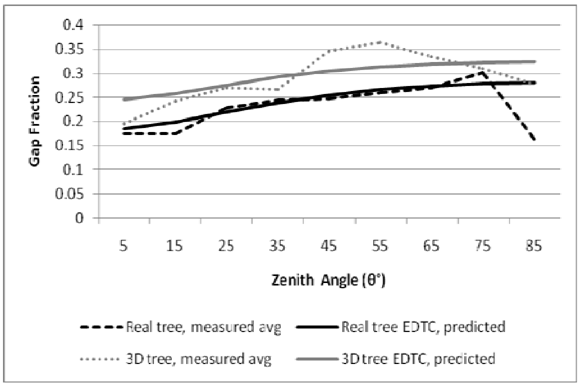

Figure 5 results of the measured gap fractions combined with the predicted ones of the produced EDTC, for both the real tree and the 3D tree

Figure 5 shows the results of the measured gap fractions combined with the predicted gap fractions of the produced EDTC, for both the real tree and the 3D tree. Table 3 shows the calculated errors; i.e., the square of the difference between the measured sky gaps of the 3D tree and the predicted gap fractions of the EDTC produced for the real tree, weighted by the proportion of valid pixels and the sector size. These illustrations show satisfactory findings and demonstrate the potential of this methodology to model trees in building performance simulation. The results can be further improved to attain better match between the 3D canopy and the real one. Because the modelled surface was parametric, modifying it was easy and fast. That is done by changing the values for the surface meshing density and the framing thicknesses to fine tune the gap fractions. After every change, a new hemispherical image is produced and analyzed.

The advantages of this method are as follows:

- One can obtain existing data of tree canopies (e.g.; LAI and gap fractions) from databases used by specialists and research centres in forestry research and agriculture authorities. This means that in many cases data acquisition from the field might not be needed, and the tree modelling procedure becomes easier.
- Using hemispherical photography in the architectural design process is very common. Architects uses hemispherical photographs to assess “site factors” that estimate the solar radiation regimes at different positions within or near buildings. It is used to analyse the influence of human structures such as buildings, to analyse the influence of topographic features such as mountains, or even to analyse the influence of window placement within a room inside a building.
- Also, to most architects and other specialists in buildings, using the computer to model a 3D objects such as a canopy surface is a common task in architectural design. This kind of work lends itself to the work environment of building design, and can be adapted easily to become part of the design process by architects and building designers.
- Because the method depends on parametric 3D object modelling, modifying the modelled canopies is relatively easy and fast. This helps to always improve the results to attain better match between the 3D canopy and the real one. It also helps to save time and effort when new objects can be quickly created by adapting previous ones (i.e., rapid prototyping).
- The model is simple and independent in its interaction with Radiance (or any other accurate simulation package). It is imported to Radiance as only a geometrical object. The material spectral properties including their color, reflective properties, and transmittance properties are added within Radiance. In this regard, it is safe and the accuracy to simulate light (direct, diffuse, and reflected) will depend on Radiance and the simulation conditions that are defined by the user including sky definitions.

CONCLUSION

A methodology that integrates measurement of tree canopy characteristics (gap fraction and leaf area density) using hemispherical photography, development of 3D objects using parametric modeling to represent tree prototypes, and the use of trees in lighting simulation programs is demonstrated. This depended on expressions that predict gap fractions of a theoretical canopy based on calculated values of Ellipsoidal Leaf Angle Distribution Parameter (ELADP) and Leaf Area Density (LD), for an assumed crown geometry that give the best fit to the measured gap fraction values, using a "least squares" technique. The gap fractions results show close agreement between the real tree and the modelled one. The maximum calculated error is 0.003. The practicality of this method makes it very desirable for use in building design and simulation. Validation of the simulation results against real measurement of lighting levels for a full scene needs to be investigated in future research.

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NOMENCLATURE

G, τ:	Gap fraction
K(θ):	Extinction coefficient at angle θ
L, LAI:	Leaf Area Index
θ:	zenith angle
ELADP:	Ellipsoidal Leaf Angle Distribution Parameter
LD:	Leaf area density
D:	Distance through the canopy

Table 1

Gap fractions of the real tree: measured from hemispherical photo and predicted (for EDTC) by the model

	Azimuth Angle									
		0°	**45°**	**90°**	**135°**	**180°**	**225°**	**270°**	**315°**	**AVG**	**EDTC**
Zenith Angle	**5°**	0.210	0.101	0.385	0.130	0.054	0.163	0.071	0.282	0.175	0.185
	15°	0.114	0.322	0.225	0.144	0.160	0.222	0.117	0.085	0.174	0.199
	25°	0.230	0.216	0.374	0.242	0.440	0.132	0.125	0.067	0.228	0.220
	35°	0.208	0.237	0.364	0.268	0.469	0.207	0.097	0.102	0.244	0.239
	45°	0.276	0.213	0.268	0.197	0.286	0.253	0.203	0.282	0.247	0.255
	55°	0.389	0.243	0.270	0.183	0.293	0.191	0.138	0.375	0.260	0.266
	65°	0.417	0.345	0.278	0.333	0.197	0.127	0.114	0.348	0.270	0.274
	75°	0.423	0.304	0.222	0.395	0.149	0.257	0.093	0.560	0.300	0.278
	85°	0.024	0.134	0.105	0.261	0.190	0.198	0.141	0.243	0.162	0.281

Table 2

Gap fractions of the 3D tree: measured from computer-generated image and predicted (for EDTC) by the model

	Azimuth Angle									
		0°	**45°**	**90°**	**135°**	**180°**	**225°**	**270°**	**315°**	**AVG**	**EDTC**
Zenith Angle	**5°**	0.209	0.195	0.184	0.198	0.199	0.205	0.183	0.184	0.195	0.245
	15°	0.262	0.247	0.226	0.244	0.249	0.241	0.217	0.244	0.241	0.258
	25°	0.291	0.267	0.264	0.259	0.290	0.267	0.261	0.255	0.269	0.276
	35°	0.262	0.263	0.311	0.261	0.263	0.257	0.250	0.266	0.266	0.292
	45°	0.336	0.341	0.422	0.333	0.324	0.331	0.341	0.335	0.346	0.304
	55°	0.347	0.355	0.369	0.369	0.363	0.369	0.374	0.359	0.363	0.313
	65°	0.336	0.352	0.323	0.335	0.337	0.335	0.326	0.333	0.335	0.319
	75°	0.303	0.331	0.320	0.300	0.320	0.302	0.297	0.310	0.310	0.322
	85°	0.271	0.271	0.279	0.270	0.294	0.267	0.272	0.290	0.277	0.324

Table 3

Calculated errors

	Azimuth Angle								
		0°	**45°**	**90°**	**135°**	**180°**	**225°**	**270°**	**315°**
Zenith Angle	**5°**	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	15°	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	25°	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	35°	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	45°	0.001	0.001	0.003	0.001	0.000	0.001	0.001	0.001
	55°	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
	65°	0.000	0.001	0.000	0.000	0.001	0.000	0.000	0.000
	75°	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	85°	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000